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Operating room and surgical team members scheduling: A comprehensive review

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A B S T R A C T

Operating rooms (OR) are one of the most expensive parts of a hospital with complex processes, and the efficient use of resources is of utmost importance. Therefore, proper management and operation of operating rooms are extremely crucial. OR scheduling ensures that the surgeries are performed at the proper time, patients are treated effectively and safely, resources are used effectively, and staff is increased in work efficiency. Furthermore, accurately scheduled surgeries are safer for patients' healing processes. This is dependent on factors such as the availability of qualified personnel at the appropriate time, the readiness of surgical equipment, and the provision of proper sterilization and hygienic conditions. Surgical team scheduling ensures that surgeries begin on time, are completed effectively, and patients are treated safely. It is also critical to reduce employee fatigue and balance the workload. As a result, integrating surgical teams into operating room scheduling problems provides significant benefits. Accordingly, 29 research articles focusing on the problem of OR scheduling, within the scope of constraints on surgical team members, scheduling strategies, uncertainties, and solution methods, are thoroughly reviewed in this study.

1. Introduction

Operating rooms are a special department of hospitals where medical interventions are performed and patients are operated on, which is a major source of revenue. Factors such as planning the necessary resources and preparations, the date of the surgery, the length of the operation, the type of surgery, and the surgical team need to be considered when planning and scheduling surgeries. Accurate scheduling and planning of surgeries and surgical teams are critical to providing the best possible care to patients. Furthermore, it offers benefits such as more efficient use of OR resources, shorter waiting times, and reduced staff fatigue and workload.

Operating room scheduling problems involve numerous difficulties in the efficient use of surgery timing and operating room resources. Inadequate resources, emergency cases, changing surgical procedures and their duration, and personnel are frequently discussed as difficulties. Operating rooms, surgical equipment, and personnel are bottleneck resources, and their use can incur problems in terms of insufficient resources during planning and scheduling. Another problem is that emergency cases can interfere with planned surgeries' timing and operating room resources' utilization. Because surgical techniques and their durations are changing, it may be essential to modify plans during the operation, and the delay of one operation may impact the schedule of subsequent surgeries. For surgeries to be successful, hospital resources such as intensive care units, laboratories, and others must be properly managed. One of the major restraints is that surgical staff is limited and comes from a variety of specialties, so they must be properly planned. Operating room scheduling problems are NP-hard because many variables, situations, and uncertainties must be resolved under all constraints (van Essen, Hurink, Hartholt, & Akker, 2012).

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There are several approaches to arranging operating rooms. Some medical facilities produce operating room charts by hand. This strategy improves communication among operating room workers, although it can be time-consuming and error-prone. Therefore, many healthcare companies use automated methods to schedule operating rooms. In the planning, timing, and defining of the tasks of operating room employees, automated operating room scheduling systems use mathematical models, simulations, and artificial intelligence technologies. This ensures that to prevent mistakes, the operating room staff's time and resources are spent efficiently. Operating room scheduling systems based on mathematical modeling and artificial intelligence also offer features such as prioritizing procedures and executing emergency surgery first. Furthermore, it is assured that the time of the operating room personnel is scheduled and that the appropriate time is allowed for the preparation of all the equipment required by the surgery, based on the kind and duration of the procedures. Efficient planning of the tasks of the operating room's staff is equally critical for operating room scheduling problems and cannot be considered separately from surgical planning. Although the surgical team is mostly anaesthesiologists, surgeons, nurses, technicians, and other employees, the team may vary depending on the kind of operation. The operating room staff's time should be planned according to the type and duration of the operation and should be used when all operating room personnel are available. Working hours, permissions, abilities, experience, skills, and interests should all be considered when assigning operating room personnel. In this manner, the surgery can be completed successfully, errors reduced, and patients treated more effectively. Scheduling is also important for the satisfaction of operating room staff, as it helps to balance the workload and reduce fatigue and stress. As a result, operating room and operating room team scheduling is a critical topic in medicine and healthcare, as well as a significant source of revenue for hospitals. Planning surgeries in advance, as well as efficient planning of the duties of the operating room team, ensures that patients are treated better. It is also critical for the satisfaction of the surgical team.

In this context, a review study was conducted on the inclusion of surgical teams that should not be overlooked in operating room scheduling problems. The methodology of the study, material collection, and analysis are discussed in the second section. The third section includes a detailed literature review. The study is completed in the fourth section by summarizing the findings and discussing future research.

2. Research Methodology

The method of this study was determined based on the research method used by Govindan et al., (2015), which is based on the definition of Mayring (2003). A research methodology, according to the definition, consists of four steps: material collection, descriptive analysis, category selection, and material evaluation (Govindan et al., 2015).

2.1 Material Collection

The material was collected from the databases ScienceDirect, Scopus, IEEE Xplorer, and Web of Science between 15.02.2023-05.03.2023. No time limit has been made and research papers published in scientific journals are included. The title, summary, and keywords were researched using keywords in search engines ("operating room scheduling" AND (“staff” OR “surgical team” OR “personnel”)). As a result of the search, 99 scientific studies were found across all databases. The research article was chosen as the paper type restriction, and a total of 80 research articles were manually examined and recorded in an electronic table for a comprehensive examination. As a result of the review, 80 articles were removed from the databases as usual, and 13 research articles involving surgical teams were included in the OR scheduling problem within the scope of the study. Then, using the Google Scholar database, a search for the same keywords was conducted, and 16 more research articles were added to the study with manual control and analyzed.

2.2 Descriptive Analysis

The study aimed to examine 29 scientific research articles published between 2008 and 2022. Fig. 1 depicts the distribution of the number of studies by year. Operating room scheduling with surgical teams was mostly published in 2015, 2016, 2018, and 2019.

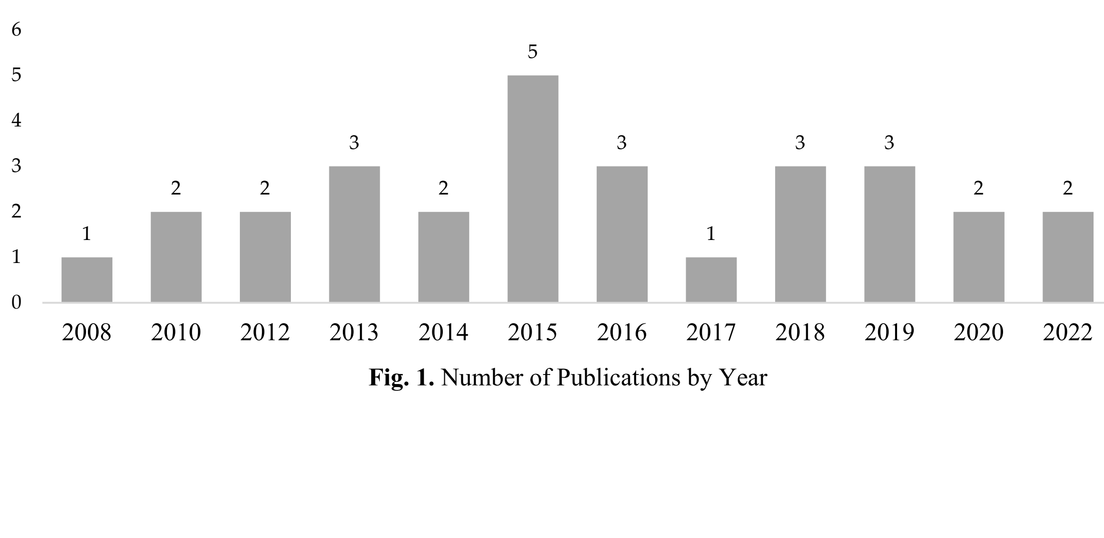

Fig. 1. Number of Publications by Year

Table 1 contains an examination of the keywords whose use and frequency were reported according to the years. As a result, the most frequently used terms among the 118 keywords were "Operating room scheduling", "OR in health services", "Constraint Programming", and "Goal programming", all of which are also used in the research method. There are 57 other terms not mentioned in the table, such as "State hospital" and "Quality".

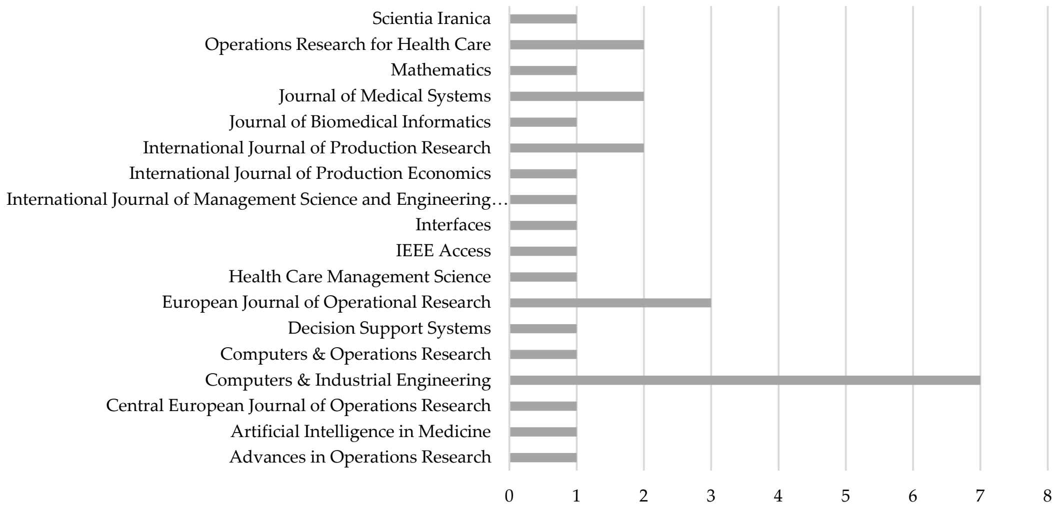

Fig. 2. Number of Publications by Journals.

The 29 publications analyzed were published in 18 journals, as shown in Fig. 2. The journals in which articles were the most published were "Computers & Industrial Engineering", "European Journal of Operational Research", "Operations Research for Health Care" and "Journal of Medical Systems". Furthermore, citation analysis was carried out, and the ten most cited papers are displayed in Table 2. Citation numbers were gathered using Google Scholar during the study's time frame. There were a total of 2308 citations to 29 articles from other papers. The paper that received the most citations was published in the "European Journal of Operational Research". Finally, Fig. 3 shows the list of authors and Figure 4 shows that keyword analysis. A total of 88 researchers conducted 29 papers.

Table 1
Keywords Number and Frequency by Years

Keywords	2008	2010	2012	2013	2014	2015	2016	2017	2018	2019	2020	2022	Total
Anesthesiologist scheduling									√				1
Approximate methods						√							1
Bicriteria optimization						√							1
Block scheduling								√					1
Constraint programming				√			√			√		√	6
Elective case scheduling						√							1
Genetic algorithm		√					√		√				3
Goal programming										√		√	2
Healthcare				√		√		√	√				4
Healthcare management		√			√								2
Hybrid genetic algorithm		√							√				2
Mathematical programming				√	√								2
Mixed integer programming		√								√	√		3
Operating room scheduling			√				√	√		√	√	√	9
Optimization			√	√									2
OR in health services	√		√							√			3
Robust optimization									√		√		2
Surgery scheduling					√	√			√			√	4
Surgical case scheduling	√			√									2
Tabu search				√									1
Operating room planning and scheduling					√	√			√				3
Nurse scheduling											√		1
Uncertainty											√		1

Table 2
Number of Citations on a Study Basis

Publications	Journal Name	Number of Citations	Rate
Pham and Klinkert (2008)	European Journal of Operational Research	451	%19,54
Fei., et al. (2010)	Computers & Industrial Engineering	347	%15,03
Roland., et al. (2010)	Computers & Industrial Engineering	204	%8,84
Meskens et al. (2013)	Decision Support Systems	181	%7,84
Vijakumara et al. (2013)	European Journal of Operational Research	140	%6,06
Saremi et al. (2013)	International Journal of Production Economics	137	%5,93
Latorre-Núñez et al. (2016)	Computers & Industrial Engineering	104	%4,46
Molina-Pariente et al. (2015)	Computers & Industrial Engineering	84	%3,63
Xiang et al. (2015)	Artificial Intelligence in Medicine	75	%3,25
Van Huele and Vanhoucke (2014)	Journal of Medical Systems	63	%2,73

2.3 Category Selection

Selected articles of this literature review are discussed and examined in this section to offer a holistic view of the latest and current studies on the integration of surgery scheduling and surgical team scheduling. While making the classification, discrimination was made as problem type, operating room facilities, strategy, scheduling time horizons, patient type, uncertainty, surgical team, solution method, and performance, and the studies were examined through this classification.

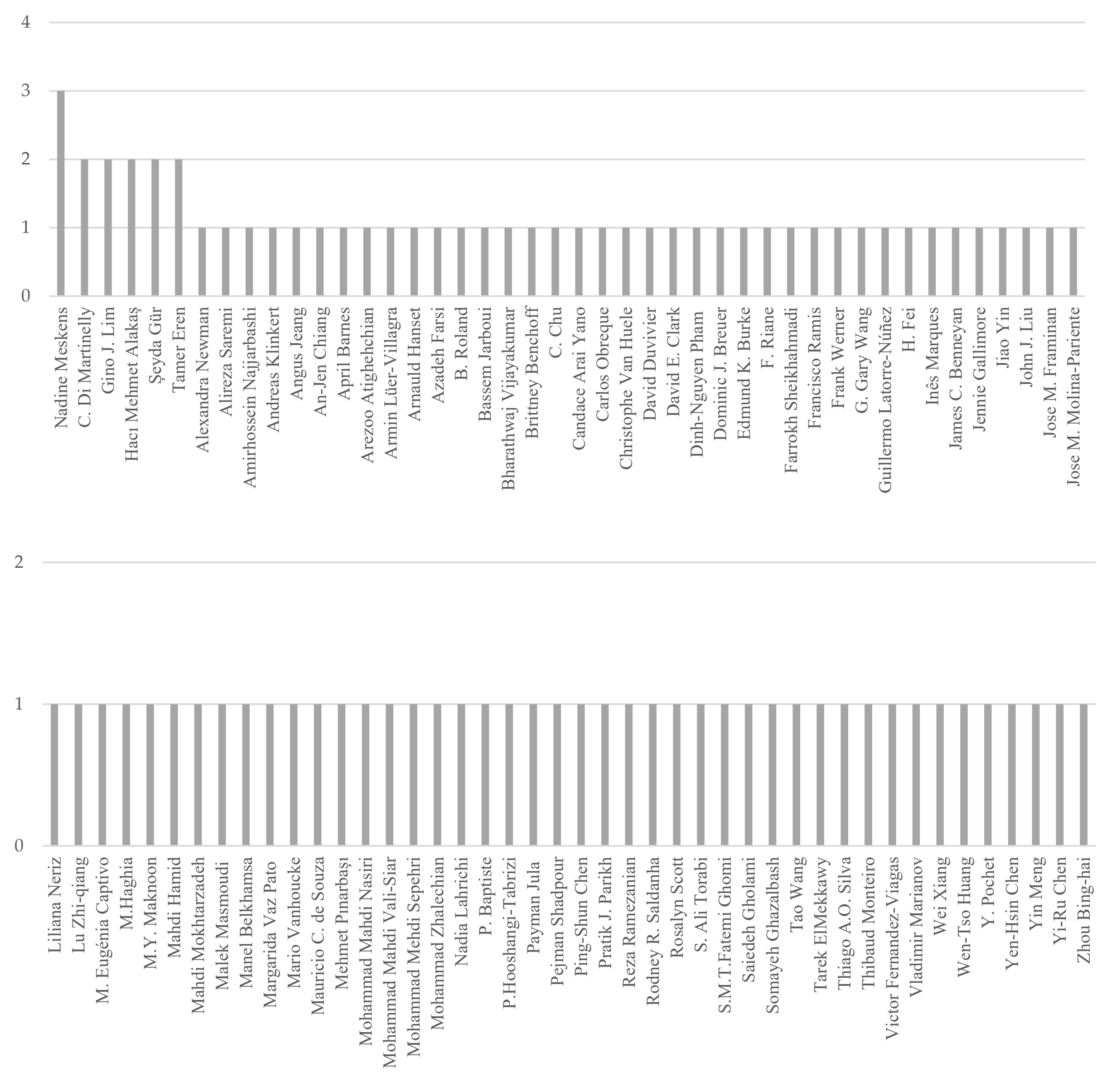

Fig. 3. Number of Publications by Authors.

Fig. 4. Keyword Cloud Analysis.

3. Detailed Analyses of the Literature

Table 3 shows detailed analysis of the 29 articles examined and their classification under the determined categories.

Table 3
Detailed Analyses of the Literature

	Problem Type	Strategy	Surgical Facilities	Time Horizon	Patient Characteristic	Uncertainty	Personnel	Solution Methods	Measures
(Pham & Klinkert, 2008)	1,3	2	1,2,3,4,5	1,3	1a,1b	-	1,3,4	1	1a,1c
(Fei et al., 2010)	1,3	1	2	3	1	-	1	1,3	1
(Roland et al., 2010)	1,3	1	-	3	1	-	1,3,4	1,3	1
(Jeang & Chiang, 2012)	1	1	-	3	1,2	-	1	1	1a,1b
(Ghazalbash et al., 2012)	1	1	-	1	1,2	-	1,2,3,4,5	1	1a
(Meskens et al., 2013)	1	2	-	1	1b	-	1,3,4	1,2	1a
(Vijayakumar et al., 2013)	1,3	1	-	3	1	-	1,3	1,2	1a
(Saremi et al., 2013)	1	1	1,2	3	1	-	1,3	1,3	1a, 2a
(Van Huele & Vanhoucke, 2014)	1,3	2	2	3	1	-	1	1	1a
(Di Martinelly et al., 2014)	1,3	1	-	3	1	-	1,3,4	1,2	1a
(Molina-Pariente, Fernandez-Viagas, et al., 2015)	1,3	1	-	3	1	-	1,2	1,2	1a
(Xiang et al., 2015)	1	1	2,3	1	1	-	1,3	1,3	1a
(Silva et al., 2015)	1,3	1	3	1	1	-	1,3,4	1,2	1a
(Marques et al., 2015)	1,3	2	1,2,3	1	1	-	1	1,2	1a
(Monteiro et al., 2015)	1	1	-	1	1	-	1,3,4	1	1a
(Latorre-Núñez et al., 2016)	1	1	2	1	1a,1b, 2	-	1,3,4	1,3	1a
(Bing-hai et al., 2016)	1,3	1	1,2,3,5	3	1	-	1,3,4	1,2	1a
(Haghi et al., 2017)	1,3	2	2	3	1	-	1	1,3	1a
(Benchoff et al., 2017)	1	1	-	3	1	-	1,3	1	1a,1b, 2a
(Vali-Siar et al., 2018)	1,3	1	1,2,3	3	1	1,3	1,3,4	1,2,3	1a
(Belkhamsa et al., 2018)	1	1	1,2,6	1	1	-	1,3,4	1,2,3	1a
(Huang et al., 2018)	1,3	1	-	1	1	1,2	1,3,4	4	1a
(Hamid et al., 2019)	1	1	2,3	1	1a	-	1,3,4	1,3	1a
(Gür et al., 2019)	1,3	2	-	3	1	-	1	1	1a, 1b, 2a, 2b
(Younespour et al., 2019)	1,3	3	-	1	1	-	1	1	1a
(Breuer et al., 2020)	1,3	2	-	3	1a,1b,2a,2b	1,2,3,4	1,3,4,5	1	1a, 2a
(Najjarbashi & Lim, 2020)	1,3	2	-	1	1	3	1	1,2	1a,2a
(Farsi et al., 2022)	1,3	1	-	3	1	-	1,3	1,3	1a,2a
(Gür et al., 2022)	1,3	2	-	1	1	3	1,2,3,4	1	1a

Problem Type: 1: Scheduling, 2: Re-Scheduling, 3: Planning
Surgical Facilities: 1: Holding Area, 2: PACU, 3: ICU, 4: Ward, 5: PHU 6: Others
Strategy: 1: Open Strategy, 2: Block Strategy, 3: Modified Block Strategy
Time Horizons: 1: Contemporaneous, 2: Very short term, 3: Short term, 4: Medium term, 5 Long term, 6: Very long term
Patient Characteristic: 1: Elective, 1a: Inpatient, 1b: Outpatient, 2: Non-Elective, 2a: Urgent, 2b: Emergencies
Uncertainty: 1: Patient Uncertainty, 2: Personnel Uncertainty, 3: Duration Uncertainty, 4: Emergency Uncertainty, 5: Others
Personnel: 1: Surgeon, 2: Assistant Surgeon, 3: Nurse, 4: Anesthetist, 5: Others
Solution Methods: 1: Mathematical Programming, 2: Heuristic, 3: Meta-Heuristic, 4: Simulation, 5: Others
Measures: 1: Improvement of Hospital Organizational, 1a: Efficiency, 1b: Quality, 1c: Others, 2: Improving the Service Provided to Patients, 2a: Efficiency, 2b: Quality, 2c: Others

3.1 Surgical Problem Type

Operating room scheduling is a complicated and difficult problem that requires careful planning to ensure the efficient use of OR resources, timely delivery of patient care, and optimal staff and equipment distribution (Zhu et al., 2019). However, unpredictable situations like delays or cancellations often interrupt the operating room scheduling and necessitate rescheduling surgery. Furthermore, the unpredictability of surgical demand and resource availability complicates the planning process. As a result, efficient OR scheduling, rescheduling, and planning strategies are critical to providing high-quality, cost-effective patient care (Hamid et al., 2019; Zhu et al., 2019). OR scheduling problems can be divided into three categories: scheduling, rescheduling, and planning (Hamid et al., 2019).

Scheduling is a sort of problem that entails determining the order in which procedures will be conducted under specific time limitations. In this setting, decisions are made such as prioritizing surgeries, choosing an acceptable surgical order, and making the best use of operating room resources (Meskens et al., 2013). Rescheduling is a problem that occurs when surgeries must be rescheduled due to unforeseen circumstances or delays in the surgery schedule. In this situation, the goal is to devise a new surgical sequence and make the best use of operating room resources (van Essen, Hurink, Hartholt, & van den Akker, 2012). Planning entails making appropriate plans for future surgery programs. In this context, it is decided how the procedures will be ordered within a particular period, which surgical equipment will be utilized, which patients will be operated on first, and how the necessary resources will be assigned to complete the surgeries. In this way, it is aimed to perform surgeries efficiently (Cardoen et al., 2010; Demeulemeester et al., 2013; Lamiri et al., 2008).

Among the scientific studies included in the study, studies that are just interested in surgical scheduling without planning are identified as (Belkhamsa et al., 2018; Benchoff et al., 2017; Ghazalbash et al., 2012; Hamid et al., 2019; Jeang & Chiang, 2012; Latorre-Núñez et al., 2016; Meskens et al., 2013; Monteiro et al., 2015; Saremi et al., 2013; Xiang et al., 2015). The studies that use both scheduling and planning types together are identified as (Bing-hai et al., 2016; Breuer et al., 2020; Farsi et al., 2022; Fei et al., 2010; Gür et al., 2019, 2022; Haghi et al., 2017; Huang et al., 2018; Marques et al., 2015; Molina-Pariente, Hans, et al., 2015; Najjarbashi & Lim, 2020; Pham & Klinkert, 2008; Roland et al., 2010; Silva et al., 2015; Vali-Siar et al., 2018; Van Huele & Vanhoucke, 2014; Vijayakumar et al., 2013; Younespour et al., 2019).

3.2 Surgical Facilities

Surgical facilities play a critical role in the scheduling of operating rooms. Surgical facilities contain the equipment, supplies, personnel, and other resources required to perform surgeries (May et al., 2011). Proper planning and management of surgical facilities during the operating room scheduling process guarantee that surgeries are completed on time and efficiently. Otherwise, procedures may be postponed or canceled due to insufficient or faulty facilities, resulting in patient discontent and financial losses.

In the scheduling process, surgical facilities are managed using various strategies such as block strategy, open strategy, or modified block strategy, in which facilities are correctly allotted (Cardoen et al., 2010; Hamid et al., 2019; Zhu et al., 2019). The number of surgeries, the number of surgeons, facility capacity, and other factors may influence the selection of these strategies. To properly manage surgical facilities, detailed data on facility usage must be recorded and analyzed. This information may include facility operation times, frequency of usage, equipment failures, and other performance parameters. This information can be used in the operating room scheduling process to ensure that facilities are utilized efficiently. As a result, proper surgical facility planning and management during the operating room scheduling process guarantees that surgeries are completed on time and efficiently. This is critical for both patient satisfaction and financial success (Cardoen et al., 2010; Hamid et al., 2019). Surgical facilities required for surgery planning have more than one form of classification. The classification to be described in this study is shown in Figure 5. The facilities required for surgical procedures can be divided into three stages (Hamid et al., 2019; Jebali et al., 2006). The first stage is preoperative. PHU beds are used as a material in it. Second, the intraoperative stage occurs in the operating room and is separated into three phases: The initial step is surgery preparation. The surgical technique is the second step. The third step is cleaning the surgery room. The surgical technique begins with patient preparation and anesthesia, followed by operation. The patient is subsequently transferred to the Post-Anesthesia Care Unit (PACU), which is designed to offer post-operative care for patients who have been sedated and are monitored in the PACU until they are entirely free of the effects of anesthesia. As a result, when scheduling the operating room, the ICU's capacity and personnel numbers should be considered to plan the postoperative care critically for patients (Hamid et al., 2019). A ward, on the other hand, is a department where patients are usually cared for after surgery. Ward is responsible for a variety of tasks following the operating room, such as ensuring patients are fully awake, monitoring wound healing, administering medications, monitoring fluid and other nutrients, and monitoring patients' overall health. Ward is critical for planning post-operative care during the operating room scheduling process. In this process, ward capacity and staff should be considered in surgery planning (Belkhamsa et al., 2018; Hamid et al., 2019; van Essen, Hurink, Hartholt, & van den Akker, 2012).

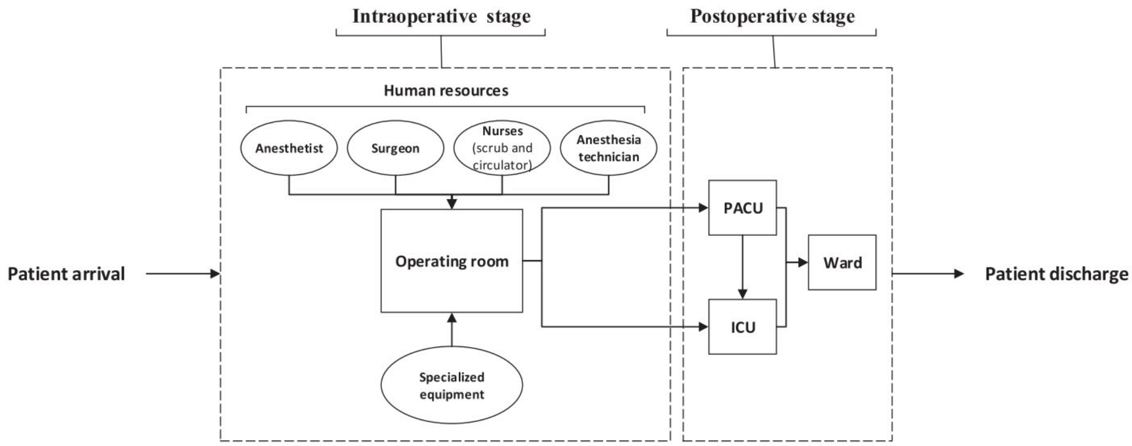

Fig. 5. Surgery Flow in Operating Room Department (Hamid et al., 2019)

3.3 Scheduling Strategy

Operating room scheduling strategies are methods of planning designed to ensure the effective utilization of operating rooms in hospitals. These strategies are developed with factors such as surgery organization, effective use of operating room resources, and adherence to the schedules of surgeons and other healthcare professionals in mind. As a result, it is a critical issue in hospital management and planning. Scheduling strategies are examined in three broad categories in this area: There are three types of strategies: block strategy, open strategy, and modified block strategy (Ghazalbash et al., 2012; Zhu et al., 2019). Open strategy is a strategy in which all surgeries can be planned in any operating room. In this strategy, appointments can be scheduled more flexibly. Since surgeries are not limited to a specific operating room, patients have more options in the appointment process. However, this strategy has the potential to reduce the effective use of OR resources (Guerriero & Guido, 2011; Hamid et al., 2019; Younespour et al., 2019; Zhu et al., 2019). The block strategy is a strategy in which surgeries are planned for a specific operating room over a period. In this strategy, surgeries are planned within a pre-assigned time frame in a specific operating room. This time frame can be of a certain length and can be divided into a specific surgical specialty. This method ensures efficient use of operating room resources and prevents operating room resources from being idle due to specific time frames allocated to each surgical specialty (Guerriero & Guido, 2011; Hamid et al., 2019; Younespour et al., 2019; Zhu et al., 2019). A modified block strategy is a hybrid of a block strategy and an open strategy. This strategy establishes block time frames for a specific operating room, while surgeries can be scheduled in multiple operating rooms. This strategy has similar benefits to the block strategy, but it is more flexible, making surgery planning easier (Guerriero & Guido, 2011; Younespour et al., 2019). Hospital administrators and operating room personnel decide on operating room scheduling strategies. This decision must be carefully considered to ensure that hospital resources are used effectively.

3.4 Scheduling Time Horizons

Surgical scheduling processes are shaped by strategic, tactical, and operational decisions made by various stakeholders such as hospital administrators, surgeons, and their representatives. These decisions are made at various time intervals, both long-term and short-term. Fig. 6 summarizes the various time intervals involved in surgical scheduling (May et al., 2011; Rahimi & Gandomi, 2021). Very long-term decisions, lasting 12-60 months, address capacity planning and allocation problems. Identifying financing and building new facilities and reallocating or changing the objectives of existing facilities are all part of this process. While these decisions are not part of the surgical programming process, they do have an impact on what is done. Long-term decisions are made when facilities are complete, and they frequently involve allocating specific blocks to specific specialties or individual surgeons. This decision-making process takes 6-12 months to plan. Following the placement of medium-term block assignments, the process of assigning and scheduling medium-term personnel begins. This entails assigning surgical time blocks to surgeons. It is usually done a few months ahead of time. The process of assigning patients to specific days and times within surgical time blocks is known as short-term surgical programming. This decision process aims to assign procedures to specific operating rooms for indefinite periods while adhering to certain constraints such as surgeon suitability, room preference, and the type of OR available for the procedure. Due to some unexpected events, the very short-term surgical programming process entails making last-minute changes to the timing plan (e.g., emergency surgeries). The surgical programming process's goal is to bring together the surgeon, anesthesiologist, nurses, surgical room, supplies, and specialized equipment by allowing enough time and a predictable workload for emergencies. Efficient surgical programming can increase operating room utilization, decrease patient wait times, and optimize hospital resource utilization (May et al., 2011; Rahimi & Gandomi, 2021).

Time horizon	How far in advance	Research areas	Examples of issues to be addressed
Very long term	12–60 months	Capacity planning, process reengineering	How many ORs to construct, layout of physical resources
Long term	6–12 months	Capacity planning, process reengineering, surgical services portfolio, procedure duration estimation	Patient flow patterns, selection of surgical providers, block assignment
Medium term	Few weeks—6 months	Capacity planning, procedure duration estimation	Staff assignment and scheduling
Short term	Few days—few weeks	Schedule construction	Procedures assigned to ORs (particular days, parts of days), number of ORs needed are determined
Very short term	24–48 hours before	Schedule construction	Last-minute scheduling into released unused block time; determining ORs to be opened; start times
Contemporaneous	Same day	Schedule execution, monitoring and control	Assignment and scheduling of emergency procedures; reassignment of ORs and rescheduling of start times as a result of emergencies, patient no-shows, cancellations, staff availability, and procedures taking more or less time than planned

Fig. 6. Time Horizons for Surgical Scheduling Problem (May et al., 2011).

3.5 Surgical Patients Characteristics

Patient characteristics are crucial in operating room (OR) scheduling problems. The classification of patients in the literature is divided into two categories: elective and non-elective (Demeulemeester et al., 2013). Elective patients are those who require surgery that can be scheduled in advance. When the patient's condition is stable and they are scheduled for a specific date, these surgeries can be performed. Elective patients are classified as inpatients or outpatients (Fujisawa et al., 2016). Inpatients are those who require at least one night of hospitalization for postoperative care. Outpatient patients are those who do not need to stay in the hospital following surgery. Non-elective patients are those who require surgery immediately and are classified as Urgent (30 min) or Emergencies (4h). Because these patients' conditions are critical, their surgeries cannot be scheduled in advance. And the waiting time is usually very short (Demeulemeester et al., 2013; Van Riet & Demeulemeester, 2015).

Elective patient scheduling necessitates queuing surgeries and making the best use of operating room capacity. As the number of elective patients grows, so does the time span of surgery completion. As a result, the operating room capacity may be underutilized. Furthermore, as the number of elective patients increases, so may the delay in non-elective patients' surgeries. Non-elective surgeries are prioritized due to emergencies. Even when elective patients' surgeries are prioritized, these patients' surgeries are typically completed over a long period. This could result in elective surgery delays and scheduling disruptions. As a result, when planning surgeries and creating the operating room schedule, the characteristics of elective and non-elective patients should be considered to make the best use of the operating room capacity.

3.6 Surgical Uncertainty

Operating room scheduling is a critical process that requires the coordination of numerous and disparate activities in a dynamic situation. Factors such as hospital staff uncertainty, time uncertainty, emergency uncertainty, and patient uncertainty can all have an impact on the timing of surgeries, resulting in increased costs and disruption to the operating room schedule. As a result, the operating room scheduling process necessitates the consideration of numerous factors, particularly in uncertain environments (Guerriero & Guido, 2011; Hamid et al., 2019; Neyshabouri & Berg, 2017; Vali-Siar et al., 2018; Zhu et al., 2019). Personnel uncertainty is a significant factor in the scheduling of operating rooms. The surgical team's availability has a direct impact on the timing and cost of the surgery. Personnel absences for holidays, illnesses, or other reasons can all have an impact on the schedule. Furthermore, the personnel's skill levels, legal restrictions, and working hours should be considered. An unexpected illness or reassignment of an operating team member may cause surgeries to be postponed or canceled (Guerriero & Guido, 2011; Zhu et al., 2019). The operating room scheduling complexity is increased by time uncertainty, which varies depending on the personnel, resources, and patient. The duration of the operation may vary on a surgical basis due to factors such as the severity of the disease, the type and techniques of the surgery, the experience of the staff, and the patient's age and health status, and these periods cannot be determined exactly in advance. The unpredictability of operation time complicates surgery scheduling and may affect the timing of subsequent surgeries, causing costs. The arrival of patients for surgery, preoperative tests, medical protocols, and other preparations, as well as the use of resources such as ICU and PACU beds following surgery, all-cause time uncertainties that have a direct impact on the efficiency of operating room scheduling (Molina-Pariente, Hans, et al., 2015; Vali-Siar et al., 2018; Zhu et al., 2019).

Although patient uncertainty influences surgery timing, it is also one of the most important factors influencing duration and emergency uncertainty. Patient delays may prevent surgeries from starting on time or shorten their duration. Furthermore, an unexpected deterioration in the patient's condition may necessitate the postponement or cancellation of surgeries. Emergency and urgent patients are other factors affecting patient uncertainty. The timing of emergency surgeries may cause other scheduled surgeries to be moved or postponed (Cardoen et al., 2010; Guerriero & Guido, 2011; Vali-Siar et al., 2018; Van

Riet & Demeulemeester, 2015; Zhu et al., 2019). For emergency uncertainties, decisions at the strategic and tactical levels are critical. Planning the blocks reserved for elective and non-elective patients under various policies such as dedicated policy, hybrid policy, or flexible policy can help to reduce or eliminate emergency uncertainties (Van Riet & Demeulemeester, 2015).

3.7 Surgical Team

Operating room scheduling problems are a complicated process that must be coordinated for hospital surgical personnel such as surgeons, assistant surgeons, secondary surgeons, nurses, anesthesia technicians, and health technicians to perform different tasks depending on the type of surgery (Breuer et al., 2020; Hamid et al., 2019). The surgeon performs tasks prior to, during, and after the operation to ensure the operation's success, while the assistant surgeon assists the surgeon. Nurses are in charge of patient care prior to, during, and after surgery, while technicians are in charge of preparing all necessary equipment for the surgical team. Anesthesia technicians, aided by the anesthesia team, prepare the anesthesia devices and assist in the preparation of the patient for anesthesia, while carriers transport patients from the operating room to other departments or hospitals. Cleaning personnel is essential for keeping the operating room clean and sanitary. Monitorization specialists monitor and record the patient's vital signs during surgery, while anesthesiologists manage the process of anesthetizing the patient during surgery. All staff members' responsibilities are intertwined, and each is critical to the success of the surgery. As a result, to solve the problem of effective and real-life operating room scheduling, it is necessary to ensure good coordination and communication among all operating room team members. Before, during, and after surgery, appropriate planning, preparation, and follow-up procedures should be carried out.

In the study, models containing only surgeon scheduling (Fei et al., 2010; Gür et al., 2019; Haghi et al., 2017; Jeang & Chiang, 2012; Marques et al., 2015; Najjarbashi & Lim, 2020; Van Huele & Vanhoucke, 2014; Younespour et al., 2019); models containing surgeon and assistant surgeon scheduling (Molina-Pariente, Hans, et al., 2015); models containing surgeon and nurse scheduling (Benchoff et al., 2017; Farsi et al., 2022; Saremi et al., 2013; Vijayakumar et al., 2013; Xiang et al., 2015); models containing surgeon, nurse, and anesthesiologist scheduling (Belkhamsa et al., 2018; Bing-hai et al., 2016; Hamid et al., 2019; Huang et al., 2018; Latorre-Núñez et al., 2016; Meskens et al., 2013; Monteiro et al., 2015; Pham & Klinkert, 2008; Roland et al., 2010; Silva et al., 2015; Vali-Siar et al., 2018) and models containing team scheduling (Breuer et al., 2020; Ghazalbash et al., 2012; Gür et al., 2022) have been determined. Involving surgical teams in scheduling problems improves many productivity indicators, such as optimizing resource use in the preoperative, intraoperative, and postoperative processes, reducing overtime wages, operating theater opening, and preparation time costs. In addition to improving hospital efficiency and quality, it has a positive impact on productivity and quality indicators such as patient safety and waiting time. Although the integration of surgical teams into operating room scheduling problems is becoming more common, there are few studies on personnel interactions and preferences. Incorporating these preferences and interactions into studies is an important step toward bringing research closer to real-world problems.

3.8 Mathematical Models and Solutions Methods

Surgical scheduling, rescheduling and planning problems have been studied in a variety of models, including linear programming (LP), mixed integer programming (MIP), bin-packing models, flow-shop models, stochastic models, and multi-criteria models, for a variety of purposes, including optimizing resource use, minimizing patient waiting time, and maximizing the use of operating rooms and personnel, and have been tabulated using review and research articles in the literature, as in show Table 4. (Demeulemeester et al., 2013; Guerriero & Guido, 2011; Hamid et al., 2019; Molina-Pariente, Hans, et al., 2015; Rahimi & Gandomi, 2021; Van Riet & Demeulemeester, 2015; Zhu et al., 2019).

Table 4
Mathematical Models and Solution Methods.

Mathematical Programming	Heuristic	Simulation	Other
Linear Programming	Constructive Heuristic	Discrete-Event	Analytical Procedure
Non-Linear Programming	Improvement Heuristic	Monte Carlo	Dedicated Branch-and-Bound
Quadratic Programming	Metaheuristic		Scenario Analysis
Goal Programming	Simulated Annealing		Markov Decision Processes
Integer Programming	Tabu Search		
Mixed Integer Programming	Genetic Algorithm		
Column Generation	Ant Colony Optimization		
Branch-and-Price	Others		
Branch-and-Cut	Dispatching-rule based Heuristic		
Dynamic Programming	Relax and Fix Heuristic		
Others	Lagrangian Relaxation		
	First Fit Decreasing (FFD)-based heuristic		
	Heuristic of first-come-first-served		
	Others		

Surgical scheduling is a complex problem when it comes to planning and managing operating rooms and resources. Therefore, to solve surgical programming problems, mathematical models are used. Many aspects of surgical programming problems can be modeled using Linear Programming (LP). Linear Programming (LP) can be used to model many aspects of surgical programming problems. This model can consider factors such as operating room usage, surgical team needs, the priority of patients, and operations. Mixed Integer Programming (MIP), like LP, can be used to solve OR scheduling problems, but it is designed to solve more complex problems. This model is particularly useful for determining the priority of patients and sequencing operations. Another mathematical model for solving operating room scheduling problems is queuing theory. This model is used to calculate the number of patients and wait times in the operating room. Simulation is a common option for operating room scheduling problems. This method considers factors such as operation timing, operation room usage times, and personnel requirements. The bin-packing model is used to assign surgeries to appropriate operating rooms, considering the size of the surgeries and the available resources. The flow-shop model is used to sequence surgeries based on each surgeon's procedure requirements (such as preparation, anesthesia, and the times required for surgery). Stochastic models are used to account for uncertainties in surgery duration and patient, personnel, and equipment arrival times. These models can assist hospitals in better managing unexpected situations and increasing operational efficiency. Multi-criteria models consider multiple goals, such as reducing patient wait times, increasing staff utilization, and lowering costs. These models allow hospitals to strike a balance between various goals and make informed decisions based on the interactions of various criteria (Demeulemeester et al., 2013; Guerriero & Guido, 2011; Hamid et al., 2019; Molina-Pariente, Hans, et al., 2015; Rahimi & Gandomi, 2021; Van Riet & Demeulemeester, 2015; Zhu et al., 2019). Overall, these various models provide hospitals with a variety of tools for optimizing surgical planning and scheduling processes and improving patient quality. Each of these mathematical models can be applied to various aspects of surgical programming problems. The model to use is determined by the characteristics of the problem and its objectives.

Pham and Klinkert (2008) used the job shop planning problem known as multi-mode blocking job shop (MMBJS) to optimize the planning of surgical cases in their study. The MMBJS problem is written as a mixed integer linear programming (MILP) problem. The model for elective patients was demonstrated with a detailed example and solved using CPLEX on practical dimensions cases (Pham & Klinkert, 2008). Fei et al. (2010) designed a weekly surgery program in an operating room environment where time blocks are reserved for surgeons rather than specialties in their study. They developed a model that was solved in two stages to maximize the use of operating room rooms, lowering the cost of operating room overtime, and reducing the unexpected spare time between surgical cases. First, the problem of determining the date of surgery for each patient was solved, considering the availability of operating rooms and surgeons. Then, using the availability of PACU beds, a daily programming problem was created to determine the order of procedures in each operating room for each day. A column-generation-based heuristic (CGBH) algorithm is used to solve the planning problem, which is defined as a set-partitioning integer programming model. The daily programming problem was treated as a two-stage hybrid flow-shop problem and solved by a hybrid genetic algorithm (HGA) based on the results obtained during the planning phase (Fei et al., 2010). Roland et al. (2010) developed a mixed integer programming (MILP) model for surgical procedure planning and programming in their study. For the model's solution, they created a heuristic solution procedure based on genetic algorithms (Roland et al., 2010). Jeang and Chiang (2012) considered the requests of the surgical team when developing the daily operating room schedule. To optimize operating room usage, a non-linear integer programming model was developed and solved using GAMS, to minimize overtime and maximize proximity between surgical team members (Jeang & Chiang, 2012). Ghazalbash et al. (2012) created a mixed integer programming (MIP) model in their study to minimize completion time. The Lexicograph method was used to solve the generated model with GAMS and CPLEX 12.1.0. (Ghazalbash et al., 2012). Mesken et al. (2013) developed a combinatorial optimization model using a matrix that quantifies the surgical team's requests between 0 and 9. JAVA language and JAVA Library CHOCO 2.1.0 were used to solve the operating room scheduling problem (Meskens et al., 2013). The problem of planning surgical cases in a public hospital with financial constraints was defined by Vijayakumar et al. (2013) as a multi-period, multi-resource, priority-based case scheduling problem as an unequal-sized, multi-bin, multi-dimensional dual bin-packing problem and modeled with mixed integer programming (MILP). To solve the problem, they devised a First Fit Decreasing algorithm (FFD). The proposed approach was compared to actual programs from a public hospital's surgical department, with a 20% reduction in the number of days and up to a 20% increase in operating room utilization (Vijayakumar et al., 2013). Saremi et al., (2013) discussed the appointment scheduling of outpatient surgeries in a multistage operating room department with stochastic service times serving multiple patient types. They proposed three simulation-based optimization methods to reduce patient waiting time, surgery completion time, and the number of surgery cancellations. To plan surgical cases, the first method is simulation-based tabu search (STS), which combines discrete event simulation and tabu search. Integer programming advanced tabu search (IPETS) and binary programming advanced tabu search (BPETS) are the second and third methods, respectively. IPETS and BPETS both improve STS by combining integer and binary programming models, respectively (Saremi et al., 2013). Van Huele and Vanhocke (2014) developed a mixed integer programming model for the Integrated Physician and Surgery Scheduling Problem (IPSSP), an operating room scheduling problem that incorporates personnel lists into surgery scheduling optimization. C++ software and CPLEX 12.5 are used to solve the developed model (Van Huele & Vanhoucke, 2014). Di Martinelly et al. (2014) used the FICO Xpress-Optimizer software program to solve a mixed integer programming (MILP) model to minimize the total cost of surgical planning. The costs associated with operating rooms and nurses' daily payments were used to estimate cost minimization. Although no relationship was found between the number of nurses required and the number of operating rooms used, simultaneous planning of nurses and surgical interventions resulted in better resource use, less overtime, and at least a 10% reduction in operating costs, according to the model results (Di Martinelly et al., 2014). Molina-Pariente et al. (2015) developed a mixed integer linear programming (MILP) model to solve an integrated operating room planning and scheduling problem involving surgical teams of one or two surgeons, where surgical times are determined by the surgeons' experience and skills. To solve the model, an Iterated Constructive (IC) algorithm was developed. Furthermore, the robustness of the obtained surgical programs was investigated using simulation (Molina-Pariente, Fernandez-Viagas, et al., 2015). Xiang et al. (2015) combined surgical and nurse scheduling. To solve the problem, they proposed a Mixed Integer Non-Linear Programming (MINLP) model and an ant colony optimization approach (Xiang et al., 2015). Silva et al. (2015) developed an integer programming (IP) model to maximize the use of operating rooms by incorporating the use of human resources into operating room scheduling problems. For the model's solution, they created an integer programming-based Relax-and-Fix heuristic (Silva et al., 2015). Marques et al. (2015) developed a bicriteria optimization model for an elective surgical planning problem, to optimize surgical unit utilization and the number of planned surgeries. To determine efficient solutions to the Bicriteria optimization problem, the minimization of a weighted Chebyshev distance to a reference point is used. They developed a heuristic procedure that was specifically designed to address the problem's objectives (Marques et al., 2015). Monteiro et al. (2015) developed a bicriteria optimization model for developing a more effective surgical team, which takes into account factors such as material and human constraints, as well as skills, with the assumption that surgeons are responsible for surgeries on elective patients. To find optimal solutions, they used the multi-objective ε-constraint method (Monteiro et al., 2015). Latorre-Núñez et al. (2016) developed a mixed integer linear programming (MILP) model for a surgical scheduling problem that considers the constraints of surgical rooms, post-anesthetic recovery rooms, surgical resources, and the presence of possible emergency surgical operations. They modified the model to use constraint programming and created a meta-heuristic based on a genetic algorithm and a heuristic to generate solutions for larger samples (Latorre-Núñez et al., 2016). Bing-hai et al. (2016) concentrate on developing the best surgical program schedule for elective patients in a variety of operating rooms, including pre-operative, perioperative, and postoperative stages. They developed an integer programming (IP) model and presented a new Lagrangian Relaxation algorithm to reduce system costs while increasing patient satisfaction. They created a Branch and Bound algorithm for solving subproblems by defining lower bounds and superiority rules (Bing-hai et al., 2016). Haghi et al. (2017) developed a mixed integer linear programming (MILP) model for the problem of simultaneous weekly planning and scheduling in operating rooms for elective patients under the constraints of recovery beds and equipment. Since the model is NP-hard, the Genetic Algorithm and Tabu Search algorithms are designed to deal with complexity and solve large-scale samples (Haghi et al., 2017). Benchoff et al. (2017) developed an integer programming (IP) model for the operating room planning and scheduling problem using the block strategy, which included both nurse and patient costs. CPLEX 12.6.0.1 was used to solve the created model. Within four weeks, the model has completed the monthly block requirements. It also optimizes the number of admitted patients, eliminating days that require extra staff and reducing the number of surgeries that are canceled due to a lack of beds (Benchoff et al., 2017). Vali-Siar et al. (2018) developed mixed integer linear programming (MILP) to solve a multi-period and multi-source operating room planning and scheduling problem under the uncertainty of operative and recovery times, with the goals of minimizing surgery delay, overtime, and idle time. Due to the model's complexity and inability to solve large-scale problems, a metaheuristic method based on genetic algorithms and a constructive heuristic approach has been proposed. Following the determination of the parameters of the solution approaches using the Taguchi method, numerical experiments based on various examples were carried out, and the results obtained from the solution of the mathematical model were compared with the results of the proposed metaheuristic and heuristic approaches. The results show that the proposed methods perform efficiently, with the heuristic approach outperforming the genetic approach (Vali-Siar et al., 2018). Belkhamsa et al. (2018) developed a combinatorial optimization model that incorporates preoperative, intraoperative, and postoperative resource constraints, to minimize the maximum end time and total spare time in the operating rooms. The model was solved using an iterative local search (ILS) approach and a hybrid genetic algorithm (HGA). Computational experiments have shown that metaheuristics outperform ant colony optimization (Belkhamsa et al., 2018). Huang et al. (2018) focused their research on the dynamic configuration scheduling problem for stochastic medical resources. They presented a Drum-Buffer-Rope (DBR) Scheduling approach to analyze which types of medical resources become bottleneck resources to optimize OR planning. Monte Carlo simulation was used to demonstrate the effectiveness of the DBR method in uncertain situations (Huang et al., 2018). Hamid et al. (2019) developed a multi-purpose constraint programming model for the scheduling problem of surgeries, to minimize total costs due to waiting times, maximize patient service and satisfaction, and maximize team cohesion. Using the MATLAB program, Non-dominated Sorting Genetic Algorithm (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO) algorithms were developed to solve the model (Hamid et al., 2019). Gür et al. (2019) focused on the operating room scheduling problem from three perspectives. Based on the block planning strategy, the first scenario aims for a balanced distribution of transactions in the operating rooms as well as effective use of the operating rooms. In the second scenario, in addition to these objectives, the orthopedic surgeon was directed to work only in the morning hours, and a balanced distribution of procedures in periods was requested. In the third scenario, it was requested that an operating room be reserved for only one area of expertise at all times. All of these scenarios are developed with integrated goal programming and constraint programming models. Using IBM ILOG CPLEX 12.6, the method results were compared and analyzed against the current situation (Gür et al., 2019). Younespour et al. (2019) developed mixed integer programming (MILP) and constraint programming (CP) models to reduce the cost of overtime and makespan and minimize overtime and makespan under the modified block strategy. Mixed integer programming (MILP) model was solved using GAMSv23.8 software, and the constraint programming model was solved using IBM ILOG 12.6 software (Younespour et al., 2019). Breuer et al. (2020) combined surgical personnel and programming decisions to create a robust optimization model to minimize the effect of predictable variability due to differences in surgical times, personnel availability, and emergencies. Mixed integer linear programming (MILP) model was created. CPLEX 12.6.1 was used to solve the problem, which was coded in Julia 0.4.6 with JuMP. Staffing, time, and resilience to emergency uncertainty all increased operating costs by 6% on average, while overtime was reduced by 68% and utilization was reduced by 6% (Breuer et al., 2020). Najjarbashi and Lim, (2020) developed a two-stage chance constraints model to solve the operating room scheduling problem under uncertainty. The IBM CPLEX solver was used to solve the model to minimize the costs associated with opening the operating room and overtime and reducing patient waiting times (Najjarbashi & Lim, 2020). Farsi et al., (2022) developed a constraint programming (CP) model to reduce completion time while increasing patient satisfaction and surgical team proximity by addressing the integrated planning of operating rooms, nurses, and surgeons. To solve the model, a hybrid NSGA-II method and multi-objective dragonfly algorithm (MODA) were developed. The results show that the CP model could achieve high-quality solutions for problem situations in less than 500 seconds with up to 150 surgeries (Farsi et al., 2022). Gür et al., (2022) developed a goal programming and constraint programming (CP) model in their study, considering the uncertainty in operation times as well as the surgeons, nurses, and anesthesiologists on the surgical team. ILOG CPLEX 12.10 was used to solve the created model (Gür et al., 2022).

3.9. Measures / Performance Criteria

Operating room scheduling performance measures are determined for surgeries to be performed more effectively and efficiently. Performance measures are also useful for comparing the effectiveness of planning and scheduling. These criteria are based on factors such as patient health and satisfaction, hospital costs, resource utilization, and staff productivity (Fujisawa et al., 2016). There are numerous performance criteria defined in the literature for operating room scheduling problems (Cardoen et al., 2010; Fujisawa et al., 2016; Hamid et al., 2019; Schouten et al., 2023). According to the studies in the literature, these criteria are classified as shown in Table 5.

Table 5
Performance Criteria for ORs.

Improvement of Hospital Organizational		
Efficiency		
	Utilization	
		Underutilization/undertime (OR, Ward, PACU, ICU)
		Overutilization/overtime (OR, Ward, PACU, ICU)
	Time	
		Overtime
		Makespan
		Waiting Time
	Throughput	
	Resources	
	Levelling	
		OR, Ward, PACU, ICU
	Preference	
	Financial	
Quality		
	Quality of care safety	
	Well-being healthcare professionals (Workload)	
Other		
Improving the Service Provided to Patients		
Efficiency		
	Time	
		Waiting Time
		Patient Deferral
Quality		
	Quality of patient safety	
Other		

First and foremost, efficient resource utilization is critical for organizational efficiency. It is intended in this context not to waste time in the operating room, intensive care unit, service, and patient care units (PACU), and to use resources as efficiently as possible. Among the performance criteria used in this direction, the sub-use or timely use of resources such as utilization, operating room, service, and PACU has an impact on organizational efficiency. Overtime, makespan, and waiting time are time criteria used to reduce patient wait times and ensure optimal resource utilization. Throughput aims to reduce patients' post-operative recovery time and increase service delivery. Resources criteria aim to use and prioritize resources in the operating room, service, PACU, and intensive care unit in an equitable manner. Over time, the leveling criteria improve efficiency and equalize resource use. Organizational efficiency is used to evaluate preferences, operating room staff, and patient preferences. Financial criteria, such as surgery costs, are another factor that impacts organizational efficiency. There are also criteria to improve the quality of patient service reception. Time criteria, such as patient waiting time and patient deferral, have an impact on the efficiency of service procurement. Quality criteria are critical for patient safety and service quality. Other performance indicators, such as patient safety, employee workload, and patient well-being, can also be assessed.

4. Conclusion and Potential Suggestions

Operating room scheduling is a complex problem that involves the scheduling and management of personnel resources to ensure that surgical procedures are planned efficiently. It is critical in this process for operating room managers, doctors, nurses, and other staff to collaborate to maximize operating room capacity and utilization. The integrated scheduling approach addresses OR scheduling problems by combining personnel and surgery scheduling. This method ensures that operating rooms are used effectively by considering a variety of factors such as surgery planning, personnel assignments, and material and equipment management. Furthermore, integrated personnel, material, and equipment scheduling and planning reduce costs while increasing efficiency. Optimizing the capacity of the operating room reduces patient wait time and improves service quality. The integrated scheduling approach improves service quality by allowing OR supervisors and surgeons to collaborate effectively. As a result, an integrated approach to operating room scheduling problems provides significant benefits in surgery planning and resource utilization. This approach enables OR supervisors, surgeons, and surgical teams to collaborate to better serve the needs of patients.

In future studies, including the surgical team's human affinities and preferences using multi-criteria decision-making techniques, as well as including uncertainty constraints on patients, staff, and time in studies, will help to obtain more realistic results for real-life planning and scheduling problems.

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